



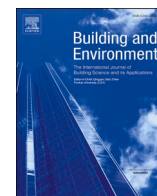
## **Drivers of winter indoor temperatures in Swedish dwellings: Investigating the tails of the distribution**

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# Drivers of winter indoor temperatures in Swedish dwellings: Investigating the tails of the distribution

Despoina Teli<sup>a,\*</sup>, Theofanis Psomas<sup>a</sup>, Sarka Langer<sup>a,b</sup>, Anders Trüschel<sup>a</sup>, Jan-Olof Dalenbäck<sup>a</sup>

<sup>a</sup> Division of Building Services Engineering, Department of Architecture and Civil Engineering, Chalmers University of Technology, SE-412 96, Göteborg, Sweden

<sup>b</sup> IVL Swedish Environmental Research Institute, Göteborg, Sweden

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## ABSTRACT

Residential indoor climate is a key factor for occupant comfort, health and wellbeing, while also affecting the buildings' energy demand. A strong focus has been traditionally placed on low winter indoor temperatures in dwellings due to their considerable health impacts. However, there is a trend towards high and stable indoor temperatures, which also have significant implications. This paper investigates the drivers of winter indoor temperatures by analysing the following three metrics of measured temperatures in a sample of 1039 Swedish dwellings: a) level, through the sample dwellings' standardised indoor temperatures at 5 °C outdoor temperature, b) daily variation, through the standard deviation of the indoor temperature and c) shape, using daily indoor temperature profiles derived from cluster analysis. The study explores the association of these metrics to building-, dwelling- and occupant-related parameters. The analysis shows that 80% of the standardised indoor temperatures were above 21 °C, with one third of the latter being above 23 °C, while 82% of dwellings had constant temperatures throughout the day. High winter indoor temperatures were more evident in middle-placed apartments in multi-family buildings connected to district heating and in better insulated single-family houses. High temperatures were also associated with experiencing draft from windows, too warm conditions in winter and difficulty to control the indoor temperature, but not with the overall thermal comfort assessment which was very positive in both the high and low temperature tails. Long-term adaptation effects, established norms and comfort expectations are discussed as important confounding factors in the development of residential indoor temperatures.

## 1. Introduction

The indoor thermal environment plays an important role in human comfort, wellbeing and health, and it influences people's overall satisfaction with their dwelling [1]. From the four environmental parameters that determine the thermal environment, i.e. air and radiant temperature, relative humidity and air velocity, temperature is considered as the most influencing factor for comfort [2]. International and National standards and guidelines provide design indoor temperatures for different building types in the form of either a comfort range or thresholds to avoid extremes (lower limit value for winter and upper limit value for summer). For residential buildings, ISO standard 17772 prescribes a range of operative temperature for the heating season between 20 and 25 °C for category II buildings (activity ~1.2 met, clothing 1 clo) [3] and a similar range is derived by the Graphic Comfort Zone of ASHRAE standard 55 [4]. CIBSE Guide A recommends 22–23 °C in living

rooms and 17–19 °C in bedrooms during winter (1.1 met, 1 clo) [5], while The Public Health Agency of Sweden suggests a range between 20 and 23 °C [6]. In energy calculation models and assessment schemes, a set-point value is used for the indoor temperature (heating demand temperature), typically 21 °C (e.g. UK's BREDEM [7] and Swedish Miljöbyggnad [8]). Indoor temperature is therefore seen primarily as a design input variable. However, great variability in indoor temperatures has been seen in real everyday home environments [9–13], especially during the heating season and in different locations around the world. It is therefore of interest to understand the reasons behind deviations in actual indoor temperatures and differences to design values, hence investigate indoor temperature as an output variable of the multiple factors that may influence it.

A large body of research on residential indoor temperatures focuses on low levels, typically caused by fuel poverty, and associated health implications of cold exposure, e.g. in the UK [14–16], Greece [17,18]

\* Corresponding author.

E-mail address: [teli@chalmers.se](mailto:teli@chalmers.se) (D. Teli).

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and Portugal [19], to name a few. At the same time, a general trend has been observed over the last century in the western world towards increased comfort expectations and warmer winter indoor temperatures, partly attributed to developments in heat supply systems, decrease of energy costs, adaptation to warmer environments, higher international building standards and improved construction of buildings [20–23]. In the UK, modelling results have suggested an increase of 1 °C per decade of the average indoor temperature in winter over the last 40 years [24], whilst measurement data have indicated an even more striking increase of up to 1.3 °C per decade from 1978 to 1996 [25]. In Sweden, average indoor temperatures were estimated at 21.2 °C in single-family dwellings and 22.3 °C in multi-family dwellings using data from 2007/08 [26, 27], whilst in 1984 the estimated averages were 20.4 °C and 21.8 °C respectively [28]. Similar average indoor temperatures during winter were found in a sample of Estonian detached houses [29] and multi-family buildings [30], i.e. 21.3 °C, but with large variations between households, with some apartments having rather high temperatures. A tendency towards warmer residential environments is also supported by the increasing evidence on the energy performance gap, where higher actual indoor temperatures than assumed based on standard recommendations, or longer heating durations, have been identified as important causes [31]. A large number of case studies that found higher actual indoor temperatures than assumed referred to low-energy or renovated homes, an illustration of licencing behaviour associated with the so-called ‘rebound effect’ [23,32–38].

Implications of maintaining high indoor temperatures in winter include increased heating demand [13] and thermal adaptation to high indoor temperatures during winter [39–42] by changing people’s expectations of the indoor environments they experience. Regarding temperature variation, experiencing constant, thermoneutral conditions has been associated with health problems, such as diabetes, cardiovascular diseases, obesity and weight gain [25,43–45]. Research has highlighted important health benefits from exposure to mildly cold or warm environments [43] and associations between high variation in experienced temperature with health satisfaction and lower risk of winter-related morbidities [46]. There are also combined comfort- and health-related benefits from experiencing thermal variation, e.g. adaptation to a wider range of accepted temperatures [2] which becomes increasingly important given the current global temperature trends and the increasing frequency of climate extremes [47]. Thermal variations have therefore the potential to contribute to future human resilience. Finally, positive experience (pleasure) occurs when mild discomfort is successfully alleviated; a phenomenon called “alliesthesia” [48,49]. Thermal stability deprives occupants of such pleasurable experiences. From an energy point of view, high and stable temperatures lead to higher heating demand. Targeting the high consumers in policy-making for energy reduction strategies has been highlighted as an efficient approach for significant energy savings [50,51].

Apart from level and variation, another temperature metric of interest is its daily profile, i.e. the shape of daily indoor temperature fluctuations [52]. A daily temperature profile may show when heating is used in a household during winter (operation schedule) and highlights patterns in people’s heating practice, information that a simple metric such as daily variation cannot provide. Studies on indoor temperature profiles also showed variations and discrepancies between assumptions and actual heating operation [12,52,53]. Together with temperature level and variation, the daily profile provides a more complete understanding of indoor temperature development in dwellings.

### 1.1. Variables associated with winter indoor temperatures

Wei et al. [54] reviewed the factors influencing space heating behaviour, hence indoor temperatures, in residential buildings and classified them into three categories: environmental factors (i.e. outdoor climate and indoor relative humidity), building- and system-related factors (e.g. dwelling type/age, building insulation, type of heating

system, heating fuel), occupant-related factors (e.g. occupant age/-gender/education level, household size, family income, house ownership) and other factors (e.g. time of day, occupancy, energy use awareness). More specifically, in a study analysing data collected in the US, homes in warmer climates were found to maintain lower winter indoor temperatures than those in colder climates [55]. Dwelling type has also been found to be an influencing factor, although with differing results, i.e. lower thermostat settings in apartments compared to other dwellings in the US [55] whilst the opposite was found in Swedish households [56].

In terms of building-related drivers, a study of a national UK survey of house temperatures identified older homes as being colder than newer homes and centrally heated homes being about 3 °C warmer than non-centrally heated homes [57]. Newer homes were found to be warmer also in a nationally representative sample of houses in New Zealand [58] and in UK studies [14,16,59]. Building age is often considered in studies as a proxy for buildings’ energy efficiency, with the latter also found to influence indoor temperature levels. Results have shown that occupants maintain higher temperatures in energy-efficient houses [14,23]. Finally, dwelling forms with greater exposed surface area and larger dwellings (with greater volumes) have been associated with lower winter indoor temperatures [59].

Regarding the influence of heating systems, a study of residential buildings in Belgrade, Serbia found that dwellings connected to district heating were significantly warmer than those with other heating systems, with an average daily living room temperature of 22.8 °C [60]. The authors attributed this to the lack of control available to the occupants (no thermostats present) and the fixed heating charges on a floor area basis, which does not provide economic motivation for energy-saving behaviour. In a UK study of social housing tower blocks, high indoor temperatures were associated with a combination of subsidised communal heating charges, building management, lack of understanding of controls and sedentary lifestyle [39,53], while in Estonian multifamily buildings, high indoor temperatures were attributed by the authors to incorrect control curves at the buildings’ substations.

Occupant-related factors have also been identified as determinants of winter indoor temperatures. In a UK study, the average daily temperature increased in homes with more occupants, with higher income and with older occupants (>64 years) [14]. Furthermore, privately and socially rented dwellings had higher indoor temperatures than owned dwellings [14,59], while unemployed households and households considered vulnerable (low income and/or in receipt of benefits) maintained lower temperatures than non-vulnerable households [59]. In a study of residential buildings in China, higher income, dwelling ownership, presence of children less than 12 years old, higher building energy efficiency, central heating and long-term thermal experience in the north of China where central heating is provided, were associated with higher indoor wintertime temperatures [61].

Other influencing factors of indoor temperature include time of the day or week, which relate to temperature adjustments according to needs, e.g. different temperatures during the day and night [55]. Analysis of daily temperature profiles in UK dwellings found a larger share of apartments and of households with night storage heaters in the dwelling cluster with stable indoor temperature throughout the day [52]. Among occupant factors investigated in the previous study, the age of the occupants and their income were also associated with the temperature profiles. Finally, energy use awareness has been found to influence indoor temperatures [54], with occupants having direct feedback on their energy use through fuel bills maintaining lower winter indoor temperatures compared to those whose heating was included in the monthly rent [56].

It is evident from the above that local context is important in determining the factors that influence heating temperatures. The Swedish context is therefore analysed in the following section.

## 1.2. Background: Swedish context

Review of literature regarding indoor air temperatures in Swedish dwellings showed that it is limited to aggregated descriptive statistics [26,62] and very little information on the factors that determine indoor temperature levels and fluctuations. This is probably due to the limited issues related to cold homes and fuel poverty present in Sweden, which is often the critical concerns addressed in such studies, as mentioned previously. Fuel poverty and excess mortality rates in Sweden are generally low compared to countries with milder climates, which to an extent is attributable to the higher thermal standards of buildings [63] but also to specific laws protecting residents from energy cut-offs when there is a risk of harm and regulations ensuring a minimum indoor temperature for all [64]. Most importantly, Sweden implements a collective charging mechanism for heating, where heating costs are fixed and included in the rent [64].

In Swedish residential buildings connected to district heating (80% of multifamily buildings [62]), the heating power is adjusted on the building level by controlling the supply temperature to the radiator system based on the outdoor temperature [65]. Such a first, building-level control based on the outdoor temperature is typically present in Swedish buildings, aiming to achieve a constant minimum indoor temperature, i.e. 21 °C. Further adjustment within individual apartments is typically possible via thermostats on the radiators. Occupants are therefore not the primary responsible actors in their apartment's indoor climate control, nor do they have a strong incentive, e.g. financial, to make adjustments if the temperature is high. In a study including surveys in multi-family buildings, most respondents considered that they did not have enough control over the heating at home [66].

Individual metering is far from widespread in Swedish multi-family buildings. In 2012, the EU-directive [67] set a requirement for individual meters to be installed by December 31, 2016, applying to heating, cooling and hot water in multi-family buildings, which was not followed in Sweden. A possibility for alternative solutions was given in the directive if "the use of individual meters is not technically feasible or not cost-efficient" [67], which was found, at a large scale, to be the case for Sweden [68]. A further challenge mentioned by Swedish housing owners is the thermal energy leakage between adjacent apartments, which questions the fairness of heat cost allocation by individual metering [69].

Heat pumps are the second most used heat supply system and most popular in single-family houses. Overall, in single-family houses, heating levels set by the outdoor temperature control can be in principle overridden by the occupants through central building-level controls and radiator thermostats.

A recent comparative survey between 5 countries, i.e. Italy, UK, Spain, Germany and Sweden, highlighted the lack of individual control practice of heating systems in Swedish households [70]. Moreover, respondents in Sweden had the lowest reported awareness of how their homes and water were heated and the lowest attention paid to household heating, with these findings assumed by the authors to be associated to the significantly higher prevalence of district heating in Sweden compared to the other participating countries. 45% of Swedish respondents in the same study also agreed or strongly agreed that homes should be warm enough to wear shorts or t-shirts in winter, and this attitude was significantly associated with the practice of keeping the heating on the whole day, although it should be again highlighted that switching the heating off through a central dwelling-level control is not an option in most district heated homes. In the above-mentioned study, distinction between multi-family and single-family buildings is not made, which would be of great interest.

In a preliminary analysis of Swedish data from winter 2007/08, a substantial part of the sample dwellings had average air temperatures above 23 °C in winter, and a very small daily variation [11]. Although previous studies point to issues of lack of control and connection to the

predominance of district heating in Sweden, there has not been any comprehensive analysis of indoor temperature levels and their possible drivers.

## 1.3. Aim of the paper

Focus in research and policies has clearly been placed on low temperatures and fuel poverty, but, based on the above literature review, the other end has significant implications too and its drivers are not yet thoroughly investigated and understood. It is important to explore why and under which conditions the issue of high and stable winter indoor temperatures occurs in dwellings and discuss their implications. This topic is addressed in this article using data from the Swedish National Survey BETSI. More specifically, the objectives of the paper are:

- To investigate indoor temperatures in Swedish dwellings considering their level, variation and shape.
- To determine the characteristics of dwellings with high and constant temperatures, compared to those with low/moderate temperatures.
- To explore the potential impact of occupant characteristics and thermal comfort/discomfort factors on indoor temperature levels and variation.

To meet these objectives, the analysis focuses primarily on the tails of the indoor temperature distribution, with greatest interest in high winter indoor temperatures.

## 2. Methods

A cross-sectional dataset was used, the so-called BETSI database. The BETSI study (Buildings, Energy consumption, Technical Status and Indoor environment) was conducted in the heating season 2007/08 and involved inspection of 1800 buildings, from which 1400 were residential. The buildings were selected as representative of the building stock from different parts of Sweden and included both single-family dwellings and apartments in multi-family buildings. The collected data include building characteristics, energy systems and energy use, measurements of indoor climate parameters and occupants' perception, satisfaction levels, health symptoms, occupancy and behavioural aspects regarding the indoor climate. The questionnaire was designed, administered and analysed by Statistics Sweden, the Swedish government agency that operates under the Ministry of Finance for producing official statistics (information on the questionnaire can be found in [71]). The results were presented in the form of descriptions and aggregated statistics of the general condition of the dwellings [26], of technical aspects of the building stock [62], and a separate analysis of occupants' survey responses [72]. The data became openly available in 2011 and a number of researchers conducted further analysis in parts of it, which covered: Holistic Indoor Environmental Quality (IEQ) satisfaction [1], health symptoms vs building dampness, mould and other parameters [73–76], IEQ measurements vs building characteristics [27]. The dataset has also been used in order to characterise and model the building stock in terms of technical properties [77,78].

### 2.1. Study sample

The initial sample consisted of approximately 1400 dwellings, i.e. single-family houses and apartments in multi-family houses. First, dwellings that were monitored during the transitional or non-heating season were excluded ( $N = 198$ ). The exclusion criteria follow Swedish recommendations for determining the heating season, i.e. the heating season ends when  $T_{out} > 11$  °C [79]. Dwellings where monitoring took place in either the entrance, dining room, kitchen or bedroom were excluded ( $N = 62$ ). The remaining sample is  $N = 1039$  dwellings and approximately 1.3 M indoor temperature readings taken either in the living room or in the - typically adjacent - hall. Based on the share of

multifamily and single-family buildings and the share of dwellings in building age groups, the new sample remains representative of the 1400 BETSI dwellings.

The indoor temperature was measured for 14 days at 15-min intervals; the outdoor temperatures were obtained from nearby municipal ambient air monitoring/meteorological stations. The validity of including in the sample the 326 dwellings where measurements were taken in the hall was tested by examining the standardised mean difference (Cohen's  $d$ ) between measurements in living rooms and halls, and the difference was insignificant (Table A in Appendix A).

The air temperature measurements were thoroughly inspected for outliers through examination of the minima and maxima of all dwelling datasets. In several cases the datasets included erroneous measurements from before installation or after collection from the dwelling. In those cases, the first or last days of monitoring were cleaned accordingly. Further cleaning involved exclusion of cases where the indoor temperature would suggest unoccupied space, e.g. indoor temperatures  $< 12^\circ\text{C}$ .

## 2.2. Study design

The study of the measured indoor temperatures comprises of three parts, i) temperature level ii) daily temperature variation and iii) daily temperature profile. The data include air temperature readings. First, the indoor air temperature is corrected for the outdoor conditions to enable comparison of the air temperature levels between dwellings, since the measurements were taken at different periods, outdoor conditions and in different locations across Sweden. Second, the average daily standard deviation of the indoor temperature is derived for each dwelling, for the analysis of their thermal variation. Lastly, the dwellings' daily temperature profiles are generated to investigate daily patterns in temperature variations.

The study follows with the association of the above indoor temperature metrics with building-, dwelling- and occupant-related variables.

### 2.2.1. Indoor temperature level: standardization of indoor temperature

The standardization of indoor air temperature for a specific outdoor air temperature follows the method used by [16,59,80]. First, the data were resampled into hourly values, as the outdoor temperatures from the meteorological stations were recorded at hourly intervals. As per the previous research, ordinary least squares (OLS) is used to generate the dwelling-individual models of the indoor temperature as a function of the outdoor temperature, including quadratic terms of the independent variable. The latter is done to cover the possibility of non-linearity in the relationship, e.g. due to cold or warm extremes [59].

Each dwelling model was based on approximately 300 pairs of hourly indoor-outdoor temperatures. Standardised indoor mean hourly temperatures with their confidence intervals were derived for  $T_{\text{out}} = 5^\circ\text{C}$ , as a typical winter temperature within the range of the data of most monitored dwellings and for comparison with previous studies [16,59,80]. The fitted models and predicted dwelling temperatures were inspected for potential bias and precision. Bias in the models was checked through inspection of fitted curves and residual plots (normal probability plots, residuals vs fitted value plots). Inspection for precision was based on the standard error of the estimate and the confidence intervals of the predicted indoor temperature at  $T_{\text{out}} = 5^\circ\text{C}$ . 244 dwellings were excluded from the analysis due to above-related issues, e.g. large scatter of air temperature measurements or insufficient measurements at  $T_{\text{out}} = 5^\circ\text{C}$ .

### 2.2.2. Daily indoor temperature variation: daily standard deviation

The mean daily standard deviation of the measured air temperature in each of the 1039 dwellings is used as a metric of its thermal variation. A dwelling's thermal variation could be influenced by the outdoor weather conditions, although this is less likely in heated dwellings in wintertime. To test this in the dataset, the relationship between the calculated standard deviations and i) the mean outdoor temperature and

ii) standard deviation of the outdoor temperature were investigated through linear regression. No relationship was found and therefore the dwelling standard deviations of the indoor air temperature are used -unadjusted for outdoor conditions- in the analysis.

### 2.2.3. Shape of indoor temperature: cluster analysis

Cluster analysis was performed to identify typical daily profiles of the investigated dwellings. Following the method applied by [52], the air temperature records for each dwelling were centralized by subtracting each day's average from the 96 measurement time points (24 h  $\times$  4 15-min time points/h). As in [52], this approach is chosen since the temperature profile is of interest here, not the temperature level. The latter is investigated through the standardised indoor temperatures (see 2.2.1).

Only weekdays are included in the cluster analysis, to maintain as similar conditions as possible. It is expected that not everyone follows the same week pattern. However, in absence of such information in the dataset, it was considered more appropriate to exclude the weekends.

Both agglomerative hierarchical (with squared Euclidean distances and the Ward's minimum variance method) [81] and K-means clustering [82] were applied for verification purposes.

### 2.2.4. Associations with building- and occupant-related variables

The variables that have been included in the statistical analysis are summarised in Table 1. The chosen statistical tests were based on the type of variables (categorical, ordinal, continuous) and their distributions (normal or non-normal), and include Chi-Square test for association, independent samples'  $t$ -test (parametric, with equal or unequal variances, as applicable) and two-sample Mann-Whitney  $U$  test (non-parametric). Statistical significance was defined as  $p \leq 0.05$ .

Both bivariate and multivariate analyses were conducted to identify the characteristics of dwellings with low and high temperatures, and to detect the most significant drivers of their differences. Multivariate analysis involved binary logistic regression, following filtering of predictor variables based on the bivariate analysis.

## 3. Results

The results are presented in three main sections, focusing on the three temperature metrics described under Methods: temperature level (3.1), variation (3.2) and shape (3.3).

### 3.1. Indoor temperature level

#### 3.1.1. Overview of temperature data

The distributions of all measurements and corresponding outdoor temperatures from meteorological stations can be seen in Fig. 1 and Fig. 2. As can be seen in Table 2, 25% of the measurements are below  $21^\circ\text{C}$  and another 25% above  $23^\circ\text{C}$ . The outdoor temperatures with the highest frequency of indoor temperature measurements were around  $5^\circ\text{C}$ .

#### 3.1.2. Standardised indoor temperatures and grouping by temperature level

As expected, the majority of the standardised indoor temperatures are well within the recommended range of  $20\text{--}23^\circ\text{C}$  of the Swedish Health Agency [6] (Fig. 3). However, compared to the design value of  $21^\circ\text{C}$  typically used in energy calculations and simulations, the predicted winter indoor temperatures are rather high. 80% of the temperatures are above  $21^\circ\text{C}$ , which is of course a positive indication of adequate winter indoor temperatures in Swedish dwellings. However, a fairly large proportion of those that are above  $21^\circ\text{C}$  (27%) are above  $23^\circ\text{C}$ .

Comparison of the distributions of predicted temperatures by type of building shows an overall higher prevalence of high temperatures in apartments compared to single-family houses [Fig. 3 (b)], and the difference is statistically significant.



**Table 1**

Variables considered in the analysis with their categories, where applicable.

Independent variable	Variable properties/categories
<i>Building characteristics</i>	
Building type	Multifamily, Single-family building
Architectural type	Swedish architectural typology, based on morphological building characteristics
Building location	City centre, city suburbs, residential neighbourhood, sparsely populated area
Level of building exposure to wind	Strong, moderate, negligible
Relation to surroundings	Completely detached, intermediate, part of building block
Construction year	Continuous variable and in following categories: Before 1960, 1961–1975, 1976–1985, 1986–1995 and 1996–2005
Average U-value incl. thermal bridging	Continuous variable, W/m <sup>2</sup> K
Glazing U-value incl. thermal bridging	Continuous variable, W/m <sup>2</sup> K
External wall U-value incl. thermal bridging	Continuous variable, W/m <sup>2</sup> K
Glazing to external wall ratio	Continuous variable, %
Heat supply system	Direct electricity, combustion boiler, electric boiler, district heating, heat pump, other
Ventilation system	Natural ventilation, extract ventilation, extract ventilation with heat pump, supply and extract ventilation, supply and extract with heat recovery ventilation
Building's geographical location (latitude)	Continuous variable, degrees [°]
<i>Dwelling characteristics</i>	
Air change rate ACH (measured)	Continuous variable, 1/h
Dwelling volume	Continuous variable, m <sup>3</sup>
Floor level (apartments only)	Basement/semi-underground, ground floor, middle floor, top floor
<i>Occupant characteristics<sup>a</sup></i>	
Age	Continuous variable, years
Gender	Male/female
Lifestyle (duration outside home)	Away 0–4 h, away 5–9 h, away ≥ 10 h
Household composition	Adults, adults and teenagers, adults and children, all three
Airing frequency	Daily, once a week, once a month, never
<i>Occupant perception</i>	
Overall thermal comfort rating	Very good, good, acceptable, poor, very poor
Thermal discomfort factors (too warm, too cold, cold floors, draft, varying temperatures, difficulty to control temperature)	Yes-often, yes-sometimes, no-never

<sup>a</sup> The survey questionnaire is available in Swedish in a report published by the National Board of Housing, Building and Planning (Boverket) [72].

For the analysis in this paper, the standardised indoor temperatures are grouped based on the quartiles of the distribution, as seen in Table 3. The analysis will focus on comparison between the ‘tails’ of the distribution, Groups Q1 and Q4, in order to determine the characteristics of dwellings which explain the conservative or potentially wasteful heating pattern.

### 3.1.3. Relationship with building-related variables

Results on the comparison of building- and dwelling-related variables between the low temperature group Q1 and the high temperature group Q4 are presented separately for the categorical and continuous variables, in Table 4 and Table 6 respectively.

The share of building type to the four temperature level groups reveals a clear trend, as seen in Fig. 4, where Group Q1 consists 80% of

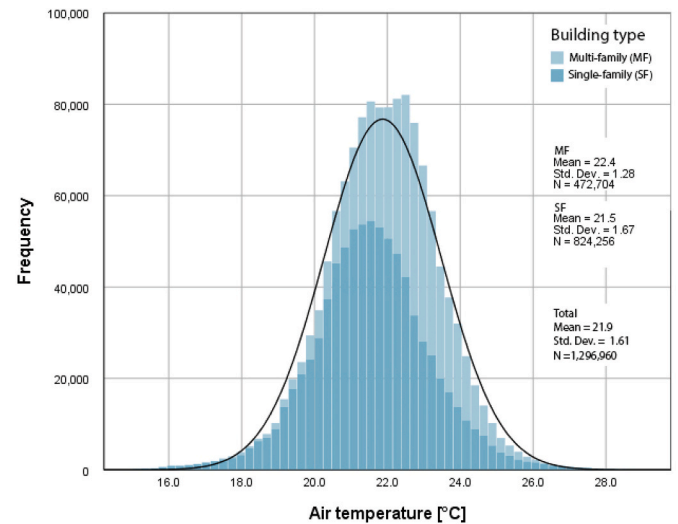


Fig. 1. Histogram of the measured indoor temperature records for the valid sample (N = 1039 dwellings).

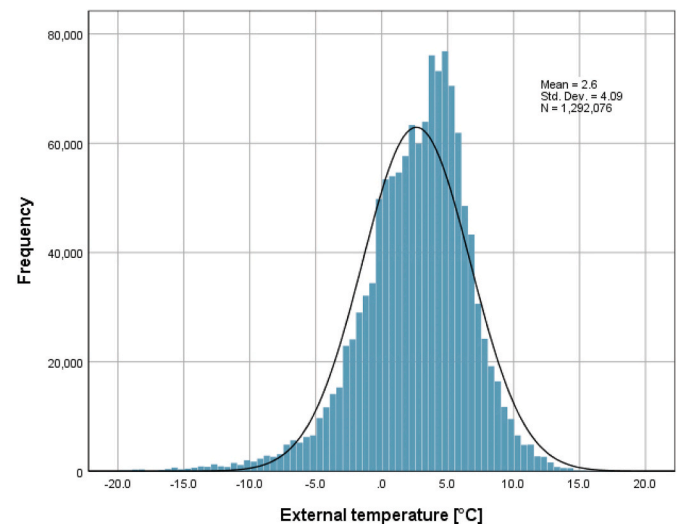
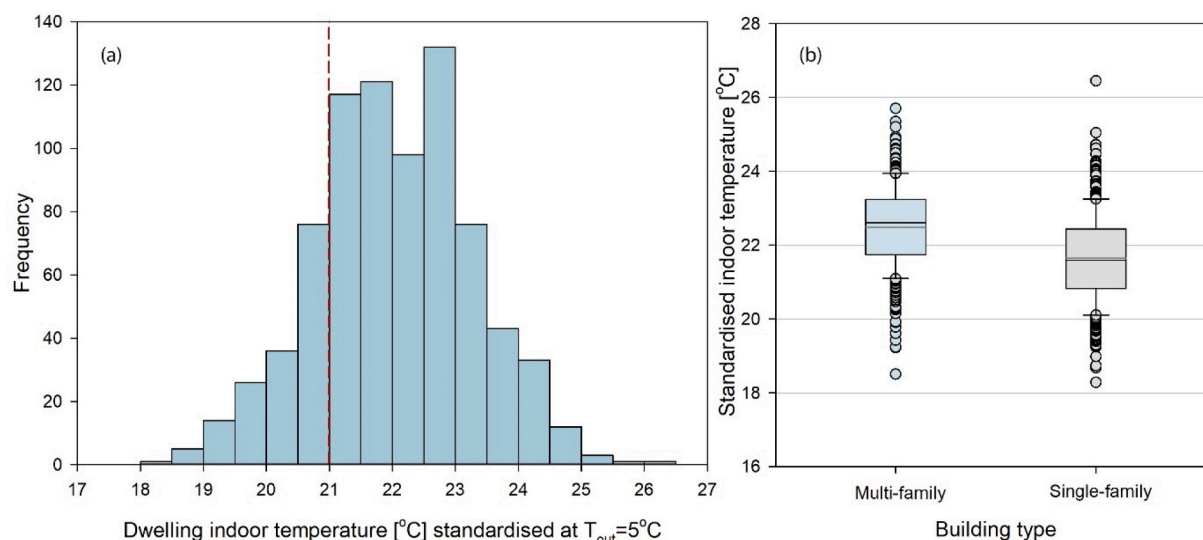


Fig. 2. Histogram of the external temperature records for the valid sample (N = 1039 dwellings).

**Table 2**

Percentiles of the measured indoor air temperatures and outdoor temperatures.

	Indoor temperature		Outdoor temperature
Percentiles	10	19.9	−2.4
	25	20.9	0.3
	50	21.9	3.1
	75	22.9	5.3
	90	23.8	7.2



**Fig. 3.** (a) Histogram of predicted dwelling hourly temperatures for 5  $^{\circ}\text{C}$  outdoor temperature (all dwellings,  $N = 795$ ), (b) Boxplots of the standardised indoor temperatures by building type (apartment in multi-family building,  $N = 352$ /single-family house,  $N = 443$ ),  $p < 0.001$ .

**Table 3**

Grouping of standardised indoor temperatures ( $T^*$ ) in quartiles.

Group	Condition	Description
Q1	$T^* < 21.2^{\circ}\text{C}$	Low indoor temperature group- conservative heating pattern
Q2	$21.2 < T^* < 22^{\circ}\text{C}$	Lower range of typical temperature group
Q3	$22 < T^* < 22.8^{\circ}\text{C}$	Upper range of typical temperature group
Q4	$22.8 < T^* < 23^{\circ}\text{C}$	High temperature group- potentially wasteful heating pattern

single-family houses which drops to 33% in the high-temperature group Q4. The relationship between temperature group and building type is statistically significant (Table 4).

In terms of construction year, it can be seen in Fig. 5 that buildings in the group with the high temperatures (Q4) are on average more recently built than buildings in group Q1 (the continuous data were used in Fig. 5). 75% of buildings in group Q4 were built after 1970, while 75% of buildings in group Q1 were built before 1985. Further analysis was conducted with the building age groups that were used in the National survey (Tables 4 and 5). The age groups refer to periods with similar building regulations. Chi-Square Tests revealed statistically significant difference between Q1 and Q4 for the entire sample and by building type. As can be seen in Table 5, the shares of dwellings within groups differ, but the trend remains clear.

Comparisons of the building's location and exposure to wind between groups Q1 and Q4 showed significant differences for the entire sample but not by building type (Table 4), most likely related to the clear association between these factors and the building type. For multi-family and single-family buildings separately, the influence of their subcategories-here denoted as architectural type-on temperature level was investigated. The standard architectural typology used in the national survey was used here, which is based on morphological building characteristics, e.g. scale, form, shape and number of storeys (categories in Swedish/not included). No statistically significant difference was

found between the groups in either of the building types.

Fig. 6 shows the proportion of each ventilation type in the groups Q1 and Q4. The larger proportion of naturally ventilated buildings in Q1 could explain to an extent the lower temperatures, together with the fact that older more leaky buildings are typically naturally ventilated. As seen in Table 4, the difference is statistically significant for the single-family houses and for the two building types combined.

The heat supply systems are also analysed for the sample and by building type (Table 4 and Fig. 7). As expected, district heating is the predominant heat supply system in the apartments, while in single-family houses the share is spread across systems. For the entire sample and for multifamily buildings, a statistically significant difference was found between the groups Q1 and Q4 (Table 4). It appears that heat supply systems play some role in the temperature level difference between the two groups, most likely related to their temperature control mechanisms.

Comparison of apartment distribution on floor levels illustrates a distinct difference between the groups, as can be seen in Fig. 8, and is statistically significant (Table 4). The share of middle-placed apartments increases as the temperature level increases, with 53% of apartments in group Q4 being on a middle floor.

Table 6 summarises the results for the building- and dwelling-related continuous variables. Comparison of the average building U-value of the investigated dwellings yielded no statistically significant difference, with averages of 0.55  $\text{W}/\text{m}^2\text{K}$  and 0.60  $\text{W}/\text{m}^2\text{K}$  for Group Q1 and Q4 respectively. However, the external envelope area of a dwelling in a multi-family building is typically much smaller compared to a single-family house, hence also its impact on the occupants and the indoor temperature. The U-value comparison by building type is therefore here more meaningful.

For the multifamily buildings, the difference in average U-value between the two groups was small (0.04) and not statistically significant. The same result was derived from the comparison of the glazing's U-value and the U-value of external walls separately. For the single-family buildings however, the difference was statistically significant for the average U-value and for the U-value of external walls. The average U-value of houses in Group Q1 is 0.53 ( $\pm 0.23$ )  $\text{W}/\text{m}^2\text{K}$  while in Group Q4 0.47 ( $\pm 0.16$ )  $\text{W}/\text{m}^2\text{K}$ .

The glazing-to-external wall ratio was not found to be associated

**Table 4**

Distribution of dwellings in groups Q1 and Q4 by building- and dwelling-related categorical variables (significance tested using Chi-Square tests).

		Q1		Q4		Sig* of difference		
Variable	Category	N	%	N	%	All	MF	SF
Building characteristics								
Building type	Multifamily	40	20	131	67	<0.001	N/A	N/A
	Single-family	159	80	65	33			
Building's age group	≤1960	55	28	30	15	<0.001	<0.01	<0.05
	1961–1975	50	25	38	19			
	1976–1985	39	20	30	15			
	1986–1995	29	15	46	23			
	1996–2005	24	12	52	28			
Building location	City centre	26	13	56	28	<0.001	0.096	0.564
	City suburbs	14	7	58	30			
	Residential neighbourhood	130	66	72	37			
	Sparsely populated area	28	14	9	5			
Building's exposure to wind	Strong	20	10	35	18	<0.05	0.122	0.162
	Moderate	126	63	129	66			
	Negligible	53	27	32	16			
Building's architectural type/form	[Swedish typologies/different between MF and SF]	–	–	–	–		0.412	0.25
Building's relation to surroundings	Completely detached	147	74	132	67	0.278	0.594	0.058
	Intermediate	23	12	24	12			
	Part of building block	29	14	40	21			
Heat supply system	Direct electricity	31	16	10	5	<0.001	<0.01	0.06
	Combustion boiler	22	11	5	3			
	Electric boiler	23	12	6	3			
	District heating	60	30	144	74			
	Heat pump	61	31	28	14			
	Other	1	0	2	1			
Ventilation system	Natural ventilation	95	50	40	25	<0.001	0.4	<0.05
	Extract ventilation	54	29	82	52			
	Extract ventilation with heat pump	16	8	19	12			
	Supply and extract ventilation	7	4	2	1			
	Supply and extract with recovery	17	9	15	10			
Dwelling characteristics								
Floor level (apartments only)	Basement/semi-underground	1	3	1	1	N/A	<0.05	N/A
	Ground floor	11	27	37	28			
	Middle floor	13	32	69	53			
	Top floor	15	38	23	18			

Notes: MF: Multifamily building, SF: Single-family building, Sig\*: significance of difference.

with the difference in temperature levels between Q1 and Q4 in the analysis by building type, with averages of 21% and 23% respectively for multifamily-buildings, and 15% and 15.5% respectively for single-family buildings (Table 6). The statistically significant difference detected for the entire sample is most likely due to the confounding effect of building type on the result.

The following analysis explores whether there is a difference in indoor temperature levels based on whether a building is located towards the North or South of Sweden. As can be seen in Table 6, no statistically significant difference was found in the latitudes between the two groups, both for the entire sample and by building type.

However, a small difference can be seen in the spread across latitudes (Fig. 9). It appears that group Q1 (low indoor temperature) buildings are concentrated in a narrower range of latitudes around the mean 58.97 (Stockholm  $\phi = 59.33$ ), while group Q4 buildings spread slightly more towards the South of the country, particularly in the case of single-family houses (Q4 SD = 2.81 while Q1 SD = 2.31, Table 6). This could be explained by the shorter heating duration in the South of Sweden, hence lower cost of heating to maintain high indoor temperatures compared to the North of Sweden.

Moving on to dwelling characteristics, the average dwelling volume for apartments in Q1 is smaller than in Q4, i.e. 165.5 m<sup>3</sup> compared to



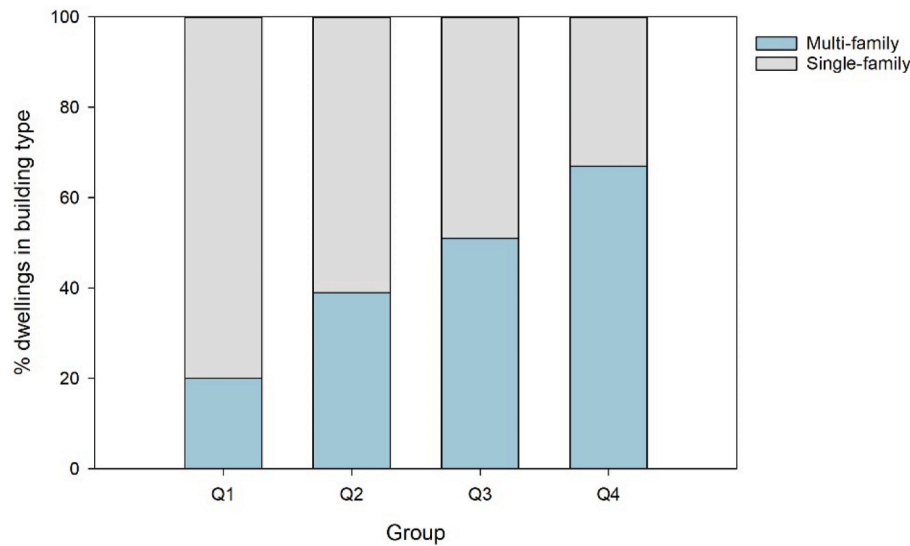


Fig. 4. Share of building type in the four temperature groups.

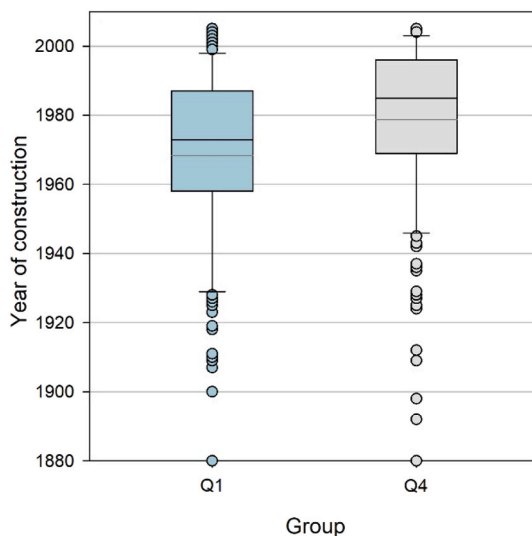


Fig. 5. Comparison of groups Q1 and Q4 in terms of year of construction, \*\*\* $p < 0.001$ .

186.6 m<sup>3</sup>, but the difference is not statistically significant. In single-family houses however, the difference is statistically significant, with the Q1 houses this time being larger than the Q4 houses, i.e. 337.3 m<sup>3</sup> compared to 300.2 m<sup>3</sup>. The most likely explanation is the difficulty and cost to heat larger houses, which leads to lower indoor temperatures.

In terms of air change rates (Fig. 10), group Q1 buildings appear to have on average slightly lower ACHs (0.40 1/h) compared to buildings in group Q4 (0.46 1/h), which is probably due to their older age and lack of continuous ventilation in most of them (Fig. 6, larger proportion of naturally ventilated buildings in Q1). The difference is statistically significant, but rather small to be conclusive.

### 3.1.4. Relationship with occupant characteristics, perception, and behaviour

Information on the occupants is provided in the occupant surveys and includes age, gender, number of adults, teenagers and children, and time spent outside home, which is used here as a lifestyle indicator. The questionnaires were filled in by one or more adult occupants. Data on all occupants are therefore not available, but of those who agreed to fill out the survey. A total of 878 responses from dwellings with standardised indoor temperatures were available for analysis, 237 belonging in the low temperature group Q1 and 181 in the high temperature group Q4. Results of the comparison between Q1 and Q4 are presented in Table 7.

Regarding gender, hours spent outside home during weekdays and household composition, there was no statistically significant difference between groups Q1 and Q4. Results also showed no statistically significant difference in the age of survey respondents between Q1 and Q4,  $t(342) = 1.110$ ,  $p = 0.268$ . It can be concluded that the indoor temperature level in this study was not associated with any of the available occupant characteristics. However, this finding may be affected by the lack of data from all dwelling residents and other issues associated with the survey procedure.

Occupants of the investigated dwellings also responded to a survey on multiple aspects of their indoor environment. Only the questions associated with the thermal environment are included in this analysis, i.e. general thermal rating (5-point scale from 'very good' to 'very poor') and experience of discomfort (3-point scale: yes-often, yes-sometimes, no-never) from too cold in winter, too warm in winter, cold floors, draft from windows, varying temperature and difficulty to control temperature. A total of 865 responses are analysed from 470 dwellings, split in the groups as follows: Q1 = 27%, Q2 = 26%, Q3 = 26% and Q4 = 21%.

The general thermal comfort rating is very positive for all standardised temperature groups, with approximately 80% of the responses being "good" or "very good" (Fig. 11). It appears that occupants' thermal preferences overall match with the thermal conditions in their homes, in agreement with adaptive comfort theory, which postulates that people adapt to the conditions they typically experience [2]. The positive votes are slightly more in the high temperature quartile Q4, but the difference is small. Overall, no association was found between temperature group and thermal comfort rating that would justify the increased temperatures as a means for improved thermal comfort.

Regarding the discomfort parameters, Chi-Square Tests ( $\chi^2$ ) revealed

**Table 5**

Distribution of dwellings in age groups by building type (MF: multi-family, SF: single-family) and total, (N: count, %: % within group) for temperature groups Q1 and Q4. Largest % within each group highlighted in bold.

Build. type	Temp. Group		≤ 1960	1961–1975	1976–1985	1986–1995	1996–2005	Total
MF	Q1	N	11	15	5	6	3	40
		%	27.5	<b>37.5</b>	12.5	15.0	7.5	100.0
	Q4	N	18	29	16	26	42	131
		%	13.7	22.1	12.2	19.8	<b>32.1</b>	100.0
	Total	N	29	44	21	32	45	171
		%	17.0	25.7	12.3	18.7	26.3	100.0
SF	Q1	N	44	35	34	23	21	157
		%	<b>28.0</b>	22.3	21.7	14.6	13.4	100.0
	Q4	N	12	9	14	20	10	65
		%	18.5	13.8	21.5	<b>30.8</b>	15.4	100.0
	Total	N	56	44	48	43	31	222
		%	25.2	19.8	21.6	19.4	14.0	100.0
Total	Q1	N	55	50	39	29	24	197
		%	<b>27.90</b>	25.4	19.8	14.7	12.2	100.0
	Q4	N	30	38	30	46	52	196
		%	15.3	19.4	15.3	23.5	<b>26.5</b>	100.0
	Total	N	85	88	69	75	76	393
		%	21.6	22.4	17.6	19.1	19.3	100.0

**Table 6**

Comparison between Q1 and Q4 of building- and dwelling-related continuous variables, including mean, standard deviation and statistical significance of difference (statistically significant difference highlighted in bold).

		Q1		Q4		
Variable		Mean	SD	Mean	SD	Sig* of diff.
<i>Building characteristics</i>						
Average U-value incl. thermal bridging	All	0.55	0.24	0.60	0.31	0.093
	MF	0.62	0.25	0.66	0.35	0.488
	SF	0.53	0.23	0.47	0.16	<0.05
Glazing U-value incl. thermal bridging	All	2.15	0.33	2.08	0.32	<0.05
	MF	2.04	0.32	2.07	0.32	0.647
	SF	2.18	0.32	2.11	0.32	0.180
External wall U- value incl. thermal bridging	All	0.34	0.31	0.31	0.27	0.262
	MF	0.35	0.33	0.33	0.31	0.720
	SF	0.33	0.30	0.25	0.15	<0.01
Glazing to external wall ratio	All	16.3%	6.9%	20.7%	9.7%	<0.001
	MF	21.1%	6.2%	23.3%	10.1%	0.203
	SF	15.1%	6.6%	15.7%	6.7%	0.550
Geographical location (latitude)	All	58.96	2.27	58.77	2.59	0.430
	MF	58.75	2.10	58.79	2.48	0.920
	SF	59.02	2.31	58.72	2.81	0.420
<i>Dwelling characteristics</i>						
Air change rate ACH (measured)	All	0.40	0.26	0.46	0.26	<0.05
	MF	0.56	0.39	0.50	0.29	0.347
	SF	0.36	0.21	0.38	0.18	0.480
Dwelling volume	All	305.55	134.35	225.90	90.64	<0.001
	MF	165.53	75.93	186.64	58.31	0.077
	SF	337.25	124.13	300.18	94.65	<0.05

Notes: MF: Multifamily building, SF: Single-family building, SD: standard deviation, Sig\*: significance of difference.

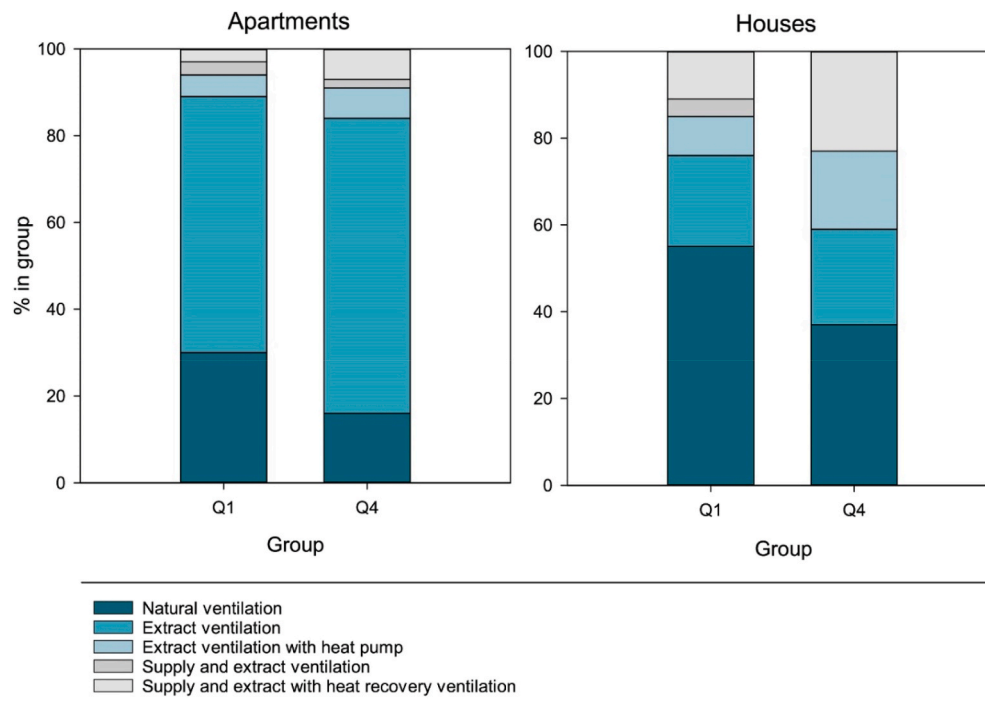


Fig. 6. Share of ventilation systems in the groups Q1 and Q4, by building type.

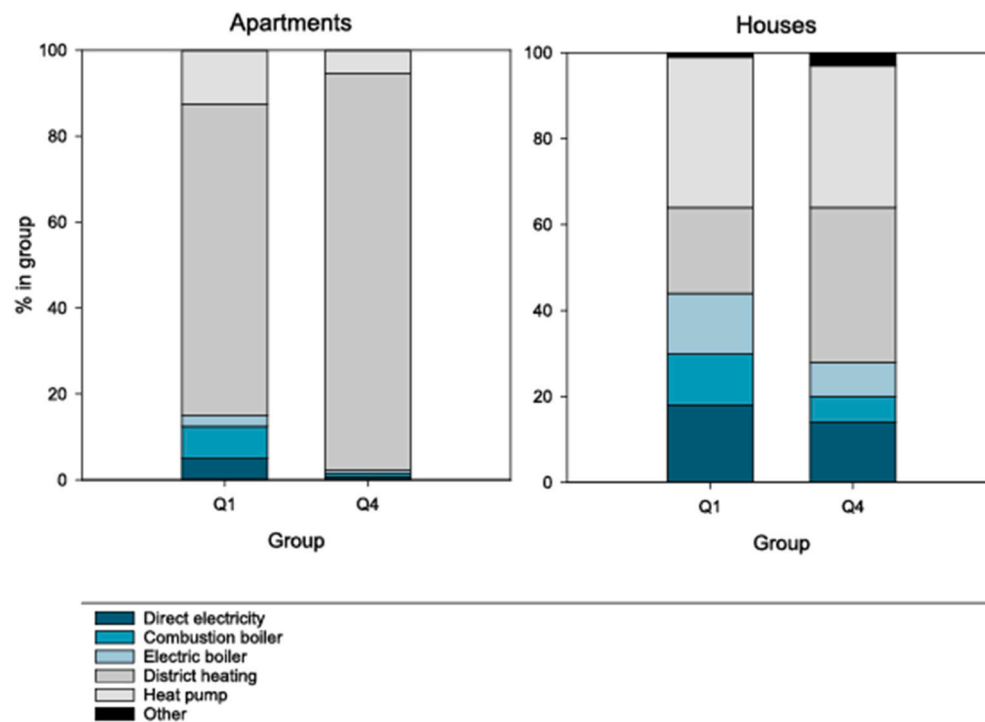


Fig. 7. Share of heat supply systems in the groups Q1 and Q4, by building type. Apartments:  $N_{Q1} = 40$ ,  $N_{Q4} = 131$ . Single-family houses:  $N_{Q1} = 158$ ,  $N_{Q4} = 64$ .

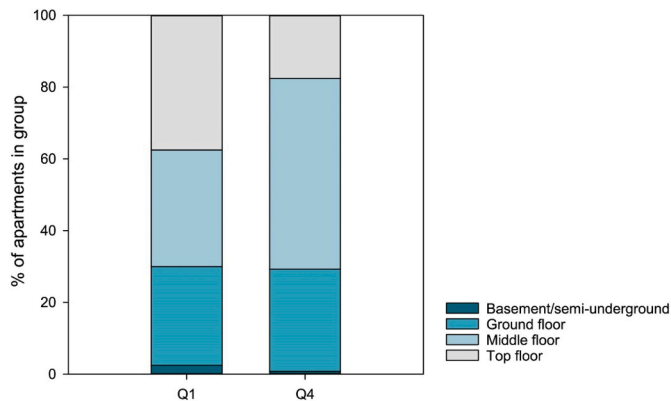


Fig. 8. Proportion of apartments in multifamily buildings on the different floor levels per group (Q1 and Q4).

significant differences between the groups Q1 and Q4 in 3 of the discomfort parameters, i.e. 'too warm in winter', 'cold floors' and 'difficulty to control temperature' (Table 7).

A larger proportion of occupants in the high temperature group Q4 reported experiencing too warm conditions in winter (21% in Q4 compared to 9% in Q1). On the contrary, a larger proportion of occupants in the low temperature group Q1 experienced cold floors. Finally, difficulty to control the indoor temperature is significantly more evident in group Q4 compared to Q1. Therefore, the high indoor temperatures in group Q4 may be attributed to an extent to difficulty in controlling indoor temperature. As a general observation however, the majority of respondents in both groups never experienced discomfort issues, which is not surprising since the temperature levels investigated in this study are within an overall acceptable range (Bar plots with the comparison of the responses to the discomfort parameters for the groups Q1 and Q4 are included in Appendix B, Fig. B).

Responses on window opening were provided in a separate, dwelling-level survey ( $N = 487$ ). Regarding window opening practice (frequency of airing), there was no significant difference between the groups,  $\chi^2(12) = 7.34$ ,  $p = 0.834$ . As can be seen in Table 8, most of the respondents in all groups (approx. 60%) report to open windows to ventilate daily. Airing behaviour can therefore not explain the difference in temperature level between groups.

### 3.1.5. Multivariate analysis

Following the bivariate analysis that revealed significant differences between the low and high temperature groups on a number of parameters, binary logistic regression is used to assess the relationship of indoor temperature level with the predictor variables adjusting for covariates. Two models were produced, one for the building- and dwelling-related variables combined and one for the occupant-related variables. This approach was followed due to the fragmented way the data collection was conducted and resulting inconsistencies between the two datasets, affecting sample sizes.

First, multicollinearity between the building-related predictor variables is investigated to detect possible strong intercorrelations through inspection of the Variance Inflation Factor (VIF) values. Collinearity was detected between the building's average U-value and the building age group and between the building type and dwelling volume. It was decided to include the building's average U-value and building type in the model. Variables in which no difference-statistical or meaningful was found in the bivariate analysis were also excluded (e.g. building's relation to surroundings and geographical location) as well as variables with different categories for multifamily and single-family buildings. Eight predictor variables and  $N = 324$  dwellings were finally included in the analysis. The logistic regression model on the occupant-related variables was generated from all 12 investigated variables and  $N = 379$  responses.

The resulting logistic regression models are statistically significant and a good fit with the data (Table 9). Model A explains 37% of the variance in temperature level and model B 22% (Nagelkerke  $R^2$ ). From the 8 predictor variables in model A, only the building type, ventilation system and heating system added significantly to the model. The building type appears to cover the effect of several of the variables, as it was also suggested in the bivariate analysis by building type. Model B

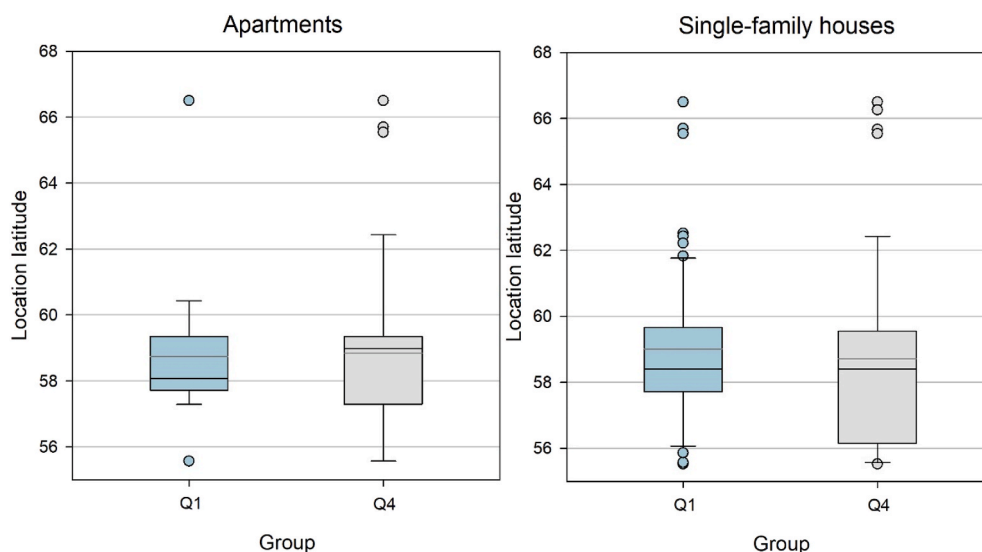
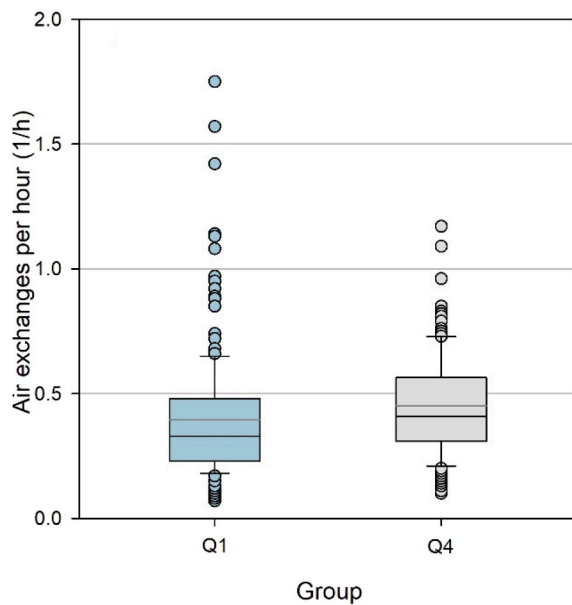


Fig. 9. Comparison of groups Q1 and Q4 in terms of the building location's latitude by building type.



**Fig. 10.** Comparison of groups Q1 (blue) and Q4 (grey) in terms of air exchanges per hour, ACH, \* $p < 0.05$ . (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

confirms the significant contribution of the discomfort parameters ‘too warm in winter’, ‘cold floors’ and ‘difficulty to control the temperature’ in the likelihood for a dwelling to belong to the high or low temperature group, while also adding ‘draft from windows’ as a significant factor. There is higher likelihood for a dwelling to belong to the high temperature group if the occupants reported to often experience draft from windows, compared to ‘sometimes’ or ‘never’. Summary tables with the variables of both models and their statistics are included in Appendix C,

Table C1 and Table C2.

### 3.2. Daily variation of indoor temperature

Results in Fig. 12 confirm the low diurnal temperature variations in Swedish dwellings previously highlighted [11], with the vast majority lying below an SD of 1 °C. Grouping of the dwellings by diurnal variation level is therefore not deemed meaningful. Only 63 dwellings (6%) had  $SD_d > 1$  °C and, as can be seen in Fig. 12(b), all but two of these correspond to single-family houses.

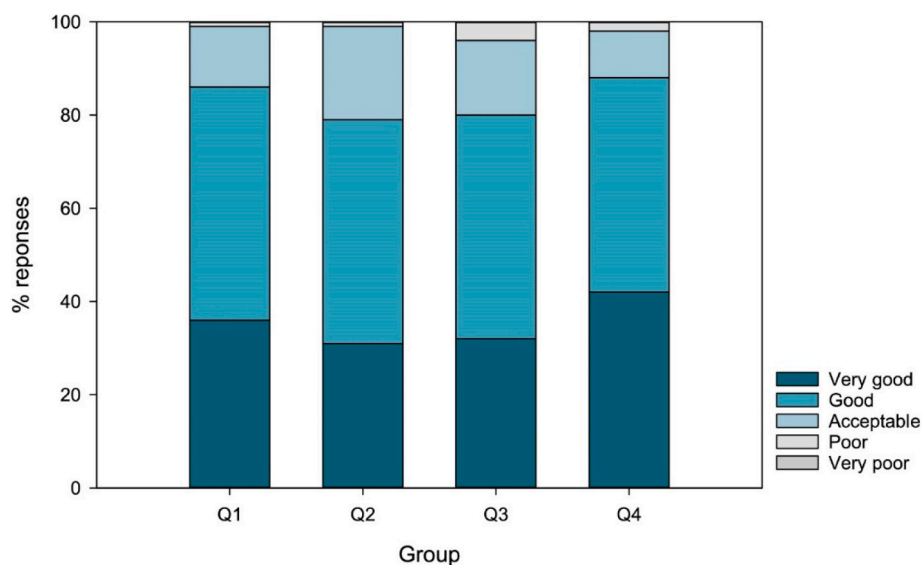
The temperature level groups’ median daily standard deviations are: 0.32, 0.32, 0.29, 0.29 respectively. The Mann-Whitney  $U$  test for non-normally distributed independent groups showed that the difference between groups is small and statistically significant only between Q1 and Q3, ( $U = 17,109$ ,  $p = 0.012$ ), and Q1 and Q4, ( $U = 15,819$ ,  $p = 0.001$ ). There does not seem to be meaningful association between temperature level and mean daily temperature variation, with the latter being low in all four temperature groups.

### 3.3. Shape of indoor temperature variation

Winter temperature profiles illustrate changes that can be associated with active temperature control and heating practices that significantly affect the temperature development indoors. This is due to the averaging of each daily time step to produce the profile, which smooths small fluctuations that could be caused momentarily by e.g. weather changes. This way, temperature profiles provide an indication of typical household heating patterns.

The cluster analysis resulted in three daily temperature profiles: (1) ‘evening peak’, (2) ‘flat line’ and (3) ‘afternoon peak’ (Fig. 13). The deviations from the average daily temperature remain in the range of  $\pm 1$  °C, unlike the findings from UK dwellings where it reached  $\pm 3$  °C [52]. This again highlights how stable indoor temperatures remain in Swedish dwellings.

It is evident that the ‘flat line’ profile dominates, with 82% of dwellings belonging to cluster 2. This is a great difference to the UK case, where 30% of dwelling belonged to that cluster, while the largest cluster was the ‘two peak’, i.e. early in the morning and evening [52]. This



**Fig. 11.** Thermal perception rating by standardised temperature group (Q1-Q4).



**Table 7**

Distribution of responses in groups Q1 and Q4 by occupant-related categorical variables (significance tested using Chi-Square tests).

Variable	Category	Q1		Q4		Sig* of diff
		N	%	N	%	
Gender	Female	119	57	91	43	0.922
	Male	116	57	87	43	
Lifestyle (duration outside home)	Away 0–4 h	81	57	62	43	0.480
	Away 5–9 h	103	55	86	45	
	Away ≥ 10 h	50	63	30	37	
Household composition	Adults	166	57	123	43	0.326
	Adults and teenagers	10	50	10	50	
	Adults and children	44	62	27	38	
	Adults and both	9	41	13	59	
Overall thermal comfort rating	Very poor	–	–	–	–	0.440
	Poor	3	43	4	57	
	Acceptable	30	63	18	37	
	Good	116	59	81	41	
	Very good	83	53	75	47	
Thermal discomfort/ too cold	Yes, often	8	73	3	27	0.218
	Yes, sometimes	83	61	53	39	
	No, never	145	54	124	46	
Thermal discomfort/ too warm	Yes, often	0	0	3	100	<0.001
	Yes, sometimes	20	38	33	62	
	No, never	215	61	140	39	
Thermal discomfort/ cold floors	Yes, often	17	81	14	19	<0.001
	Yes, sometimes	89	70	39	30	
	No, never	130	49	133	51	
Thermal discomfort/ draft windows	Yes, often	6	46	7	54	0.204
	Yes, sometimes	45	66	23	34	
	No, never	185	56	147	44	
Thermal discomfort/ varying temperature	Yes, often	5	50	5	50	0.322
	Yes, sometimes	124	61	79	39	
	No, never	107	54	91	46	
Thermal discomfort/ difficulty to control temperature	Yes, often	9	37	15	63	<0.05
	Yes, sometimes	53	52	50	48	
	No, never	172	61	110	39	

Notes: Sig\*: significance of difference.

shows the large differences in dominant heating practices between countries, e.g. continuous heating in Sweden and intermittent heating in the UK.

The second largest cluster is number 3, the ‘afternoon peak’ [N = 130 (13%)] while the smallest is cluster 1, the ‘evening peak’ [N = 59 (6%)]. These two clusters with more variable temperature profiles consist mainly of single-family houses (Table 10). As with the low temperature level group Q1, this suggests a more conservative heating practice in

these houses, where heating is likely controlled according to demand. Cluster 2 of the ‘flat line’ profile consists of a more equal share between the two (42% apartments, 58% houses).

Due to low numbers of dwellings in clusters 1 and 3, it was decided to merge them together into C11, representing the variable temperature profiles. C12 remains the ‘flat line’ temperature profile. The analysis is done separately for dwellings in multi-family buildings and single-family houses. The aim is to investigate whether these two different

**Table 8**

Responses on airing frequency by temperature level group and for the entire sample.

		Airing frequency				Total
		Daily	Once a week	Once a month	Never	
<b>Q1</b>	Count	74	26	11	18	129
	% within Quartile	57.4%	20.2%	8.5%	14.0%	100.0%
<b>Q2</b>	Count	80	20	11	17	128
	% within Quartile	62.5%	15.6%	8.6%	13.3%	100.0%
<b>Q3</b>	Count	73	22	14	15	124
	% within Quartile	58.9%	17.7%	11.3%	12.1%	100.0%
<b>Q4</b>	Count	70	14	9	13	106
	% within Quartile	66.0%	13.2%	8.5%	12.3%	100.0%
<b>Total</b>	Count	297	82	45	63	487
	% within Total	61%	17%	9%	13%	100.0%

**Table 9**

Model coefficients, significance and goodness of fit tests and case classification.

Model	Chi-square	df	p	Nagelkerke R <sup>2</sup>	Hosmer- Lemeshow p	% cases correctly classified
Model A: building-related variables	104.378	18	p < 0.001	0.369	0.311	77
Model B: occupant-related variables	66.543	25	p < 0.001	0.216	0.634	67

heating practices can be associated with available building, dwelling or occupant characteristics that were selected as relevant.

For multifamily buildings, no meaningful or statistically significant difference was found in buildings' construction year, average U-value, measured ACH and floor level between the two clusters. Similar results were derived for single-family buildings, apart from the average U-value. The average U-values were 0.47 W/m<sup>2</sup>K for cluster Cl1 and 0.51 W/m<sup>2</sup>K for cluster Cl2,  $t(323.6) = -2.064$ ,  $p = 0.04$ . This means that houses with constant temperatures have on average worse building fabric, although the difference is quite small to be conclusive. Architectural type was found to be associated with the clusters in the case of multifamily buildings only,  $\chi^2(11) = 42.07$ ,  $p < 0.001$ . A larger proportion of small-scale multifamily buildings (e.g. apartment villas, terraced houses split into apartments, etc.) is seen in cluster Cl1, possibly explained by more individualised heating controls in such buildings.

For multifamily buildings, a significant difference was found in the installed ventilation systems between clusters [ $\chi^2(4) = 17.77$ ,  $p = 0.01$ ], with the main difference being the higher percentage of exhaust air heat pumps in Cl1 (20% compared to 4% in Cl2) and lower percentage of the exhaust ventilation. For the single-family houses, there was almost no difference in the distribution of ventilation types in the two clusters. Similarly, there was no statistical or meaningful difference in the distribution of heat supply systems between Cl1 and Cl2 for both apartments and houses.

Regarding occupant perception responses, no difference was found in the overall thermal comfort rating between clusters. From the discomfort parameters investigated (see section 3.1.4), the only parameter with a meaningful and statistically significant difference between the two clusters was the 'difficulty to control temperature',  $\chi^2(2) = 9.77$ ,  $p = 0.008$ . The share of respondents that voted experiencing this often or sometimes was 5% higher in the flat-line cluster, which is allocated to "no, never" in cluster Cl1. The small difference is likely

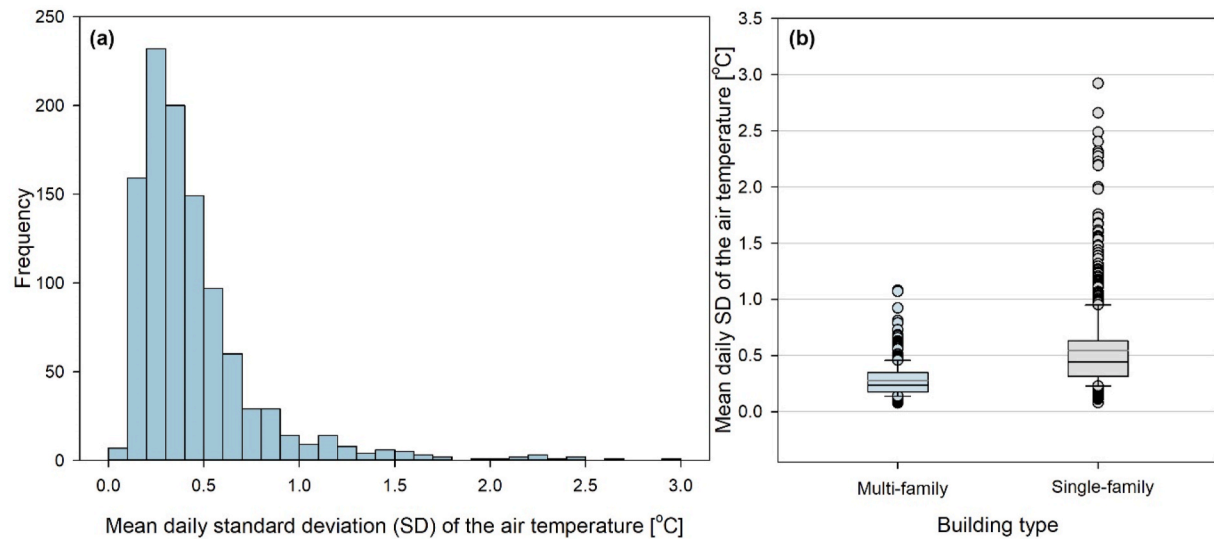
related to occupants resorting to other means to improve comfort when feeling warm, e.g. lowering clothing levels, than trying to adjust the radiator temperature, as has been confirmed before [83]. However, even though small, the difference is an indication of the role temperature control plays in daily temperature development. Household composition was not found to be a significant factor in cluster allocation, i.e. the presence of children in the household did not lead to variable temperature patterns.

#### 4. Discussion

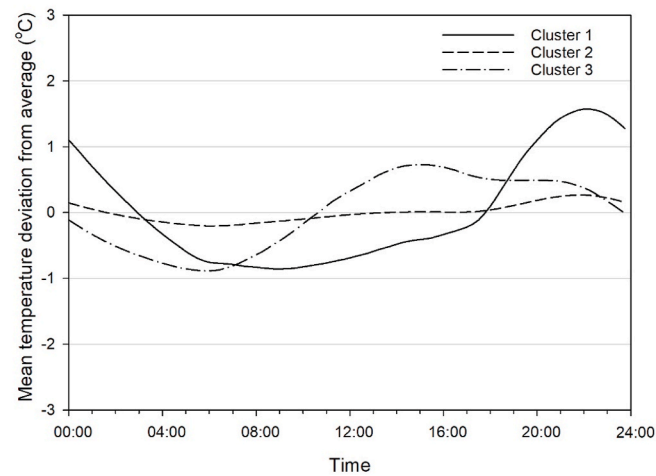
The results clearly indicate a tendency towards rather high and stable indoor temperatures in Swedish dwellings. Given the potential positive effects of variable indoor temperatures and the increased time spent at home, which has further increased after the outbreak of the covid-19 pandemic, a question arises as to whether this tendency should be maintained.

A clear difference was identified in temperature levels between apartments and single-family houses. The predominance of single-family houses in the low temperature group is most likely related to the larger heated area/volume in houses and the fact that residents are more aware of the cost of heating compared to those living in apartments, where heating costs are charged on a floor area basis and included in the rent. This issue was previously identified in UK social housing apartment blocks with the same billing strategy [53,84] and in district heated dwellings in Belgrade [60]. It should be noted that the billing strategy is the same regardless the tenure status (owned or rented) of the apartment, hence the tenure status does not affect this result. The above also explain the statistically significant contribution of the heating system to different indoor temperature levels for the entire sample and for multifamily buildings.

The analysis revealed higher indoor temperatures in middle-floor



**Fig. 12.** (a) Histogram of the dwellings' mean daily standard deviation (all dwellings,  $N = 1039$ ), (b) Boxplots of the mean daily standard deviation by building type.



**Fig. 13.** Average profiles of the three clusters (weekdays only). (1) 'evening peak', (2) 'flat line' and (3) 'afternoon peak'.

**Table 10**

Number and % of apartments and single-family houses in each of the three clusters.

		Cluster			Total
		1	2	3	
Apartments	N	4	354	20	378
	%	7%	42%	15%	
Single-family houses	N	55	496	110	661
	%	93%	58%	85%	
Total	N	59	850	130	1039
	%	6%	82%	12%	

apartments. This suggests that the high temperatures may be due to balancing problems in the building, with middle-floor apartments experiencing much warmer conditions than those at the top floor. In this case, the high temperatures are a combination of technical inefficiency (unbalanced radiator system to account for differences between apartments, e.g. less external wall area in intermediate apartments) and lack of occupant control. The latter could be due to lack of a central apartment-level control, ineffective/non-functioning controls (thermostats), occupants' lack of awareness and knowledge on their use, lack of financial incentive to lower the temperature, or combinations of these.

The building envelope of houses with high winter indoor temperatures was found to be on average better insulated than of those with lower winter indoor temperatures, which is most likely related to the so-called rebound effect [38,50] where occupants increase their comfort standards in better performing buildings, counteracting some of the benefits from energy efficiency improvement (in our case, long-term building stock improvement). Higher indoor temperatures could be chosen in certain cases by occupants to compensate for poor envelope properties and local discomfort, e.g. due to draft or radiant effects. This hypothesis is supported by the significance of experiencing draft from windows in the logistic regression model and higher ACHs found in the high temperature group, although the difference was small.

A quite surprising finding in this study was that single-family houses were prevalent at an equal share as apartments in the 'flat line' profile and at one third share in the high-temperature group. The premise was that individually paid heating and sole control over the residence would minimise such thermal conditions in single-family houses. High temperatures in certain single-family houses can be partly explained by the heat supply systems used, i.e. control behaviour and billing practice in district heated houses (20% of houses in high temperature group, most likely in urban areas) and licencing behaviour in houses heated by efficient heat pumps (18%). Another possible explanation for high and stable temperatures in single-family houses is the lack of knowledge on how to adjust their systems' settings, as these are most often set by professionals during installation. The finding could also be the result of common practice and established norms, i.e. consideration of constant temperatures as the ideal conditions [20], and habituation, as research has found that childhood and early adulthood experiences influence later energy consumption practices [85]. People that have lived in households heated through district heating-compared with others with individual heating-have been found to have a tendency to use more energy today [86]. It is possible that some of the residents in single-family houses replicate heating practices from a previous residence, e.g. apartment, are not aware of possible indoor climate control strategies or prefer to maintain high temperatures since they are in control.

From an energy and environmental perspective, maintaining moderately high winter indoor temperatures in district heated homes may be seen as a minor concern when heat supply is rather clean, as is the case in Sweden, where district heating is supplied largely by biomass and waste [87]. However, based on previous studies [39,40], long-term exposure to such warm and stable conditions at home may lead to thermal adaptation and, as a consequence, to higher sensitivity to temperatures deviating from those experienced at home. This may result in increased dissatisfaction with lower-yet in principle acceptable-indoor temperatures at e.g. the workplace or other everyday environments. If higher indoor temperatures are pursued in those environments in response to occupant complaints, then the issue could be transferred to buildings with much higher demand, greater difficulty to achieve the requested indoor temperatures or with a less 'clean' energy supply. Such gradual effects have been previously documented in

historical accounts of changes in comfort standards [88]. A changing climate with more extreme winter conditions and cold waves would also make it challenging to achieve indoor temperatures at the high end of the acceptable range. Finally, adaptation to high winter temperatures contributes to their acceptance as the norm, which in turn contributes to making reduction of indoor temperature the energy saving measure with the highest level of barriers and lowest socio-technical momentum, although being one of the most effective [89]. While temperature reduction may be seen as an unnecessary measure when the energy supply is clean, issues of peak load, increasing energy demand and embodied carbon of the clean energy constitute it worthwhile of consideration.

The high and stable winter indoor temperatures found in this analysis agree with survey findings from Swedish respondents on limited individual control practice, low reported awareness of household heating and preference for warm enough conditions to wear shorts or t-shirts in winter [70]. From the above, there is indication that a vicious cycle is created, where lack of motivation, encouragement and means to control the indoor climate leads to limited such practice, minimising, as a consequence, people's heating knowledge, awareness and understanding of potentially energy wasteful practices. This lack of energy awareness may compromise the effectiveness and uptake of new energy systems and control strategies, as confirmed with the attempt to implement smart metering [90], individual metering [69,91] and demand-side management (load shifting in space heating) [66] in Swedish multi-family buildings.

From our analysis and the previous findings on attitudes in Swedish households [70], two behaviours arise as being most likely associated with the overall high and stable temperatures in Swedish dwellings and the associated excess heating demand, i.e. the limited use of indoor climate controls and the use of low clothing levels. The cause-effect relationship however cannot be determined from the available data used here, i.e. whether the high and stable temperatures are the result of a desire to wear lighter clothes for convenience, or the inability to use the heating system controls (e.g. due to malfunction or lack of knowledge and awareness) led to the need for lighter clothing. Our results indicate that high temperatures are related to the heat supply system (i.e. its central control mechanism and collective charging for heat) and in certain cases to system balancing issues, in which case the initial cause is of socio-technical nature and occupant behaviour comes to sustain the problem. This is not to say that the heat supply system is responsible for the high and constant temperatures, but rather its central temperature control and inherent lack of user involvement.

None of the available variables appeared to be adequately associated with the clusters as indicators of heating practice, which is most likely related to the strong dominance of the flat-line cluster in the Swedish sample. There is also lack of data and occupant responses on availability and use of heating controls, which would be most relevant in this analysis. The absence of such information in the National survey is also indicative of the limited focus placed on dwelling-level heating control. There are however aspects of behaviour and individual decisions that determine the shape of indoor temperature, with apartments in the same building belonging to different clusters found in 8 multifamily buildings. This depth of analysis however could not be achieved with the available data.

The extensive BETSI dataset used in this analysis, which is the outcome of the last Swedish National survey of its kind, provided interesting insights on the indoor thermal conditions in Swedish dwellings, but it comes with certain limitations. The dataset is 13 years old, which limits its use to the analysis of relationships and drivers of patterns, rather than the characterisation of the building stock. The

number of data for generating the individual dwelling models for the derivation of the standardised temperatures and the different outdoor temperature ranges of their monitoring periods led to exclusion of a large number of dwellings. Moreover, the exclusion of dwellings based on individual model prediction accuracy meant that dwellings with variable indoor thermal conditions were excluded from the corresponding analyses. This is a limitation of the method, but inevitable since nationwide data are used. Finally, there are limitations associated with the measurement protocol of the National survey, e.g. monitoring of air temperature instead of operative temperature, measurements taken only in one location/room, unknown occupancy duration that led to standardised temperatures based on the entire dataset of each dwelling rather than reported or monitored occupied hours. Finally, inadequate coupling between measurements and survey responses, which were conducted at different periods, unnecessarily reduced the number of cases for analysis. A new National survey campaign appears to be necessary, including an improved protocol design and implementation.

## 5. Conclusions

This paper aimed to provide insights on the factors that determine winter indoor temperatures using a Nationwide dataset of Swedish dwellings. For the analysis, standardised indoor temperatures at  $T_{out} = 5\text{ }^{\circ}\text{C}$  were derived to allow for comparison between dwellings monitored at different periods, in different locations and outdoor conditions. 80% of the standardised temperatures were above  $21\text{ }^{\circ}\text{C}$ , with nearly 30% of these being above  $23\text{ }^{\circ}\text{C}$ , which is rather high for the heating season and for a cold climate country. Cluster analysis revealed that 82% of the investigated dwellings maintained stable temperatures throughout the day.

From the building- and dwelling-related factors, the main drivers of winter indoor temperatures were found to be the building's type and age, heat supply system, ventilation system, apartment floor level and in single-family houses only-average U-value. High winter indoor temperatures are more evident in middle-placed apartments in multi-family buildings connected to district heating and in better insulated single-family houses. None of the occupant characteristics investigated, i.e. age, gender, lifestyle and household composition, could explain the dwellings' temperature levels. From the local discomfort factors,

experiencing too warm conditions in winter, draft from windows and difficulty to control the indoor temperature appear to be related to high indoor temperatures, while the latter is also associated with constant temperatures.

The findings highlight the importance of efficient indoor climate controls, both at the building and dwelling levels. Although the results point to the heat supply system as a main driver of indoor temperatures, it is in fact its central control strategy, balancing issues and billing mechanism with lack of occupant engagement that underlie this finding. Occupants should be able to adjust their home's thermal conditions to avoid experiencing 'too warm' in winter or resort to lower clothing levels, and they should be aware of their household's heating. Improved interaction between people, buildings and systems can help maintain appropriate and acceptable levels of winter indoor temperatures.

Although less critical than unacceptably low indoor temperatures, high and stable winter indoor temperatures have negative long-term implications beyond the mere increase of heating energy use. The latter is anyway not a great concern in a country with one of the highest shares of energy from renewable sources, although peak demand issues still exist. Long-term health and comfort issues, as well as thermal adaptation effects are more critical here, with potentially significant implications for energy saving measures based on occupant behaviour change and for human resilience in the future. Increasing and stabilising winter indoor temperature trends and their causes should therefore be considered in a wider context and with a future perspective, as a challenge that requires further attention in research and policymaking, in alignment with relevant UN Sustainable Development Goals.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A

To test the validity of including in the sample the 326 dwellings where measurements were taken in the hall, their difference to measurements taken in the living room was investigated both for the entire sample and by building type the dwelling belongs to (multi-family vs single-family). Due to the large sample sizes and the small differences of the means (Table A), the standardised mean difference (Cohen's  $d$ ) is examined as a measure of the effect size of the difference.

**Table A**  
Mean air temperature by location the measurements took place.

Sample	Living room	Hall	Cohen's $d$
All	22.15 ( $\pm 1.52$ )	21.74 ( $\pm 1.63$ )	0.298
Multi-family buildings	22.45 ( $\pm 1.22$ )	22.43 ( $\pm 1.33$ )	0.019
Single-family buildings	21.54 ( $\pm 1.67$ )	21.56 ( $\pm 1.70$ )	0.021

As can be seen in Table A, Cohen's  $d$  is fairly small and becomes negligible when controlling for building type. It appears that the difference in the mean between measurements taken in the living room and those taken in the hall is practically insignificant. The building type has a clear effect on the indoor temperature levels, as further analysed in the paper.



## Appendix B

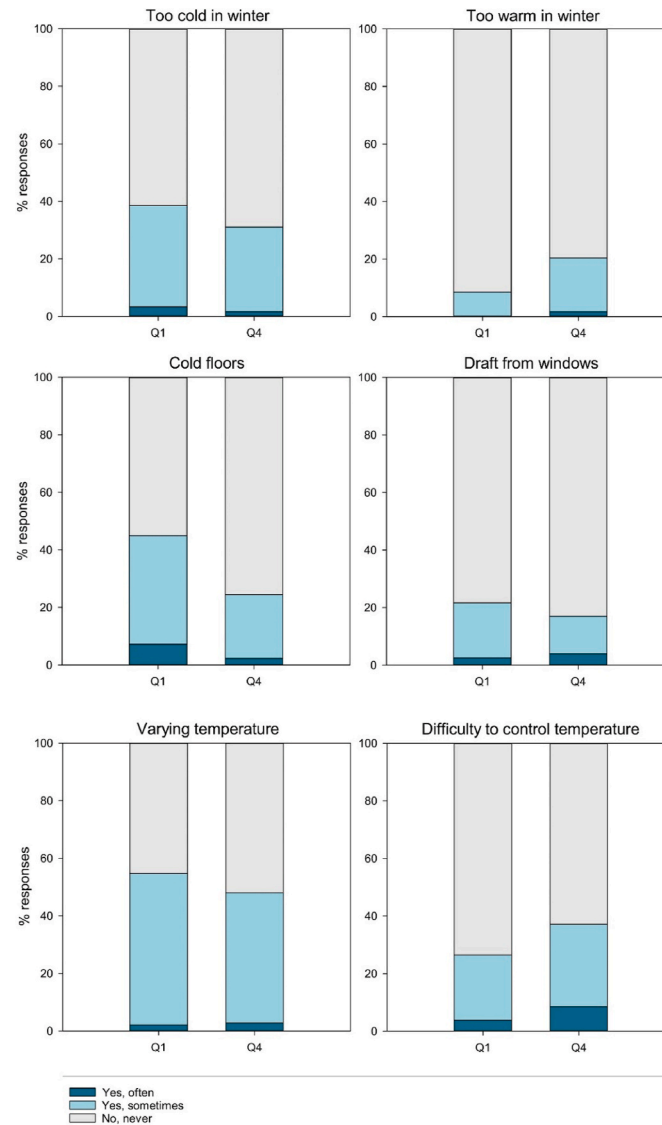


Fig. B. Comparison of the responses to the discomfort parameters for the groups Q1 and Q4.

## Appendix C

Table C1

Results of binary logistic regression of building-related factors and temperature level: regression coefficients B, p-values, Odds-ratios Exp(B) with confidence intervals (N = 324). Odds ratio above 1 higher chance of belonging to high temperature group, Odds ratio below 1 lower chance of belonging to high temperature group.

Ref. Cat.		B	p-value	Exp(B)	95% C.I. for Exp(B)	
					Lower	Upper
MF City centre	<b>Bdg type: SF</b>	−1.295	<b>0.003</b>	0.274	0.117	0.642
	<b>Building location</b>		0.208			
	Suburban	0.974	<b>0.043</b>	2.650	1.031	6.813
	Residential neighbourhood	0.459	0.352	1.582	0.602	4.158
Strong exposure	Sparsely built	0.111	0.866	1.118	0.307	4.070
	<b>Exposure to wind</b>		0.134			
	Moderate	−0.752	0.065	0.471	0.212	1.047
	Negligible	−0.889	0.064	0.411	0.161	1.052
Exhaust vent.	<b>Ventilation system</b>		<b>0.023</b>			
	Exhaust and supply	−1.552	0.181	0.212	0.022	2.059
	Exhaust/supply and HR	0.655	0.210	1.925	0.692	5.356
	Exhaust air heat pump	1.139	<b>0.024</b>	3.125	1.163	8.395
	Natural ventilation	−0.261	0.461	0.770	0.385	1.542

(continued on next page)

Table C1 (continued)

Ref. Cat.		B	p-value	Exp(B)	95% C.I. for Exp(B)	
					Lower	Upper
Direct electricity	<b>Heating system</b>		<b>0.005</b>			
	Combustion boiler	0.097	0.892	1.102	0.272	4.466
	Electric heating	−0.408	0.571	0.665	0.162	2.730
	District heating	1.448	<b>0.006</b>	4.253	1.522	11.881
	Other	2.287	0.091	9.850	0.693	139.953
	Heat pump	0.412	0.441	1.510	0.530	4.307
	<b>Glazing to ext. Wall ratio</b>	0.016	0.460	1.016	0.974	1.060
	<b>ACH of dwelling</b>	−0.376	0.493	0.686	0.234	2.013
	<b>Average U-value</b>	−0.409	0.511	0.664	0.196	2.251
	Constant	0.051	0.956	1.052		

Table C2

Results of binary logistic regression of occupant-related factors and temperature level: regression coefficients B, p-values, Odds-ratios Exp(B) with confidence intervals (N = 379). Odds ratio above 1 higher chance of belonging to high temperature group, Odds ratio below 1 lower chance of belonging to high temperature group.

Ref. Cat.		B	p-value	Exp(B)	95% C.I. for Exp(B)	
					Lower	Upper
Female	<b>Age</b>	−0.018	0.053	0.982	0.964	1.000
	<b>Gender: Male</b>	0.113	0.629	1.120	0.707	1.774
0–4 h	<b>Time away from home</b>		0.062			
	5–9 h	−0.012	0.968	0.988	0.542	1.802
	≥10 h	−0.766	<b>0.050</b>	0.465	0.216	1.000
Poor	<b>Thermal comfort rating</b>		0.508			
	Acceptable	−0.786	0.439	0.455	0.062	3.338
	Good	−0.341	0.737	0.711	0.097	5.212
	Very good	−0.071	0.946	0.932	0.121	7.155
Yes, often	<b>Too cold in winter</b>		0.283			
	Yes, sometimes	1.378	0.124	3.968	0.685	22.999
	No. Never	1.466	0.114	4.330	0.705	26.590
Yes, often	<b>Too warm in winter<sup>1</sup></b>		<b>0.004</b>			
	Yes, sometimes	−19.290	0.999	0.000	0.000	
	No. Never	−20.548	0.999	0.000	0.000	
Yes, often	<b>Cold floors</b>		<b>0.005</b>			
	Yes, sometimes	0.916	0.207	2.499	0.603	10.346
	No. Never	1.650	<b>0.021</b>	5.207	1.280	21.180
Yes, often	<b>Draft from windows</b>		<b>0.041</b>			
	Yes, sometimes	−1.871	<b>0.020</b>	0.154	0.032	0.748
	No. Never	−1.303	0.089	0.272	0.060	1.222
Yes, often	<b>Varying temperature</b>		0.568			
	Yes, sometimes	−0.585	0.467	0.557	0.115	2.696
	No. Never	−0.357	0.665	0.700	0.139	3.520
Yes, often	<b>Difficulty controlling temp</b>		<b>0.005</b>			
	Yes, sometimes	−0.760	0.249	0.468	0.128	1.704
	No. Never	−1.638	<b>0.016</b>	0.194	0.052	0.733
Daily	<b>Airing frequency</b>		0.350			
	1/week	−0.505	0.150	0.603	0.303	1.200
	1/month	0.126	0.763	1.134	0.501	2.564
	Never	0.240	0.516	1.271	0.617	2.620
Adults	<b>Household composition</b>		0.073			
	Adults + teenagers	0.005	0.993	1.005	0.335	3.011
	Adults + children	−0.791	<b>0.035</b>	0.453	0.217	0.945
	Adults + both	0.654	0.251	1.923	0.629	5.876
	Constant	21.938	0.999	3369*10 <sup>6</sup>		

<sup>1</sup> Quasi-complete (partial) separation is detected in variable 'too warm in winter', therefore estimates for its dummy variables cannot be considered. This result does not affect the maximum likelihood for other predictor variables.

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